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OPTIMAL SHIP BERTHING PLANS

by

Katie Podolak Thurman

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Thesis Advisor Gerald G. Brown

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Optimal Ship Berthing Plans

by

Katie Podolak Thurman
Lieutenant, United States Navy
B.S., United states Naval Academy, 1983

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ABSTRACT

A ship berthing plan assigns surface vessels a berth prior to their port entrance, or reassigns ships once in port to allow them to accomplish in a timely manner maintenance, training, and certification events which build readiness for future operational commitments. Each ship requires different services when in port, such as shore power, crane services, ordnance, and fuel. Unfortunately, not all services are offered at all piers. At present, ship berthing plans are manually prepared by a port operations scheduler and often result in unnecessary berth shifts, which puts ships out of action for several hours.

An extensive user-friendly computerized optimization model is developed and tested to assist the schedulers in the creation of a berthing plan which minimizes port loading conflicts, thus promoting fleet readiness through berthing stability. Norfolk Naval Station is used as an example because it exhibits all the richness of berthing problems the Navy faces.

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I. INTRODUCTION

While most ships' missions are executed at sea, their inport time is essential to maintain a high degree of material readiness and crew morale. A key to maintaining this is an efficient ship berthing plan. A ship berthing plan assigns surface vessels a berth prior to entering port or reassigns ships once in port "to accomplish a progression of maintenance training and certification events which build readiness for future operational commitments". (Wing, 1986, p.8) These events include, but are not limited to, combat systems maintenance, tests, and training, amphibious inport deck evolutions and other inport functions relevant to an individual ship class (COMNAVSURFLANT, 1987). In this study, the Navy's largest Naval Base is analyzed and modeled: Naval Station Norfolk, Virginia (NAVSTA NORVA), exhibits all features required by other bases. A computerized optimization model is developed and tested to assist the schedulers in the creation of a berthing plan which minimizes port loading conflicts, thus promoting fleet readiness through berthing stability.

The mission of the U.S. Navy, as set forth in Title 10, U.S. Code is:

> ...to be prepared to conduct prompt and sustained combat operations at sea in support of U.S. national interests; in effect, to assure continued maritime superiority for the United States. (NWP-1, 1978. p. 1-3-1)

Vice Admiral John S. McCain, Jr., U.S. Navy, emphasizes in "Command at Sea", that the Commanding Officer of a United States naval ship must understand his ship's particular goal, mission, personnel and readiness as well as the Navy's overall objective and mission. (Cope, 1966, p.vii)

"Supporting military strategy involves...having units properly manned, trained, equipped, and supported." It is the shore establishment's responsibility to "support the operating forces in terms of personnel, material, supply, and fiscal procurement; training; maintenance; and planning and operational guidance." (NWP-1, 1978, pg. 11-2-1)

An inport period achieves several goals (Wing, 1986, p.8):

1. Enhance material condition of the ships through periods of maintenance in port at the unit (shipboard), intermediate, and shipyard levels;

2. Ensure crew proficiency through formal shore-based training;

3. Certification of public and crew safety and crew proficiency in the operation of installed equipment and systems;

4. Provide adequate homeport time between operational periods in order to enhance morale;

5. Conduct inspections and certifications mandated by public law.

Prior to the port arrival of a commissioned naval ship or fleet auxiliary ship, the Commanding Officer sends a message to the appropriate naval authority stating the logistic requirements (LOGREQ) of his ship during the period in port (NWP-7, 1983, p. 7-1). This LOGREQ specifies any requests a

ship may have due to upcoming inspections, operational commitments, maintenance requirements or any other consideration the Commanding Officer identifies.

Port operation ship berthing schedulers review logistic requirements, quarterly employment schedules and squadron requests for all home-based and visiting ships, and make berth assignments based on fleet requirements and port capabilities. Factors considered in berth assignments include: pier service requirements, deployment status, special operational tests, ship and berth characteristics, as well as crane requirements for on- or off-loading supplies.

These considerations must be taken into account since each berth is unique in its capabilities: for instance, shore power and crane services available, depth and length of slip, fuel or ammunition loading capability and fendering system. (Papworth, 1988)

An optimal ship berthing plan which minimizes port loading problems would require that all possible berths for each vessel be examined and "the one which best promotes fleet readiness while minimizing conflict between the inport goals would be chosen." (Wing, 1986, p.9) As a practical matter, this is impossible for a human scheduler to do. There are simply too many details to consider over time, and comparison of the "goodness" of alternate plans is problematic.

In order to assign ships to berths that offer required services while minimizing the number of berth shifts required, a high-speed computer should be utilized, berthing rules and ship priorities formally quantified, and an appropriate measure of effectiveness developed. The model developed herein meets these criteria. (Wing, 1986, p.9)

A. PROBLEM SCOPE

The focus of this thesis is on berthing surface ships assigned an inport period at the Naval Station Norfolk, although the methods developed here may be extended to other bases and stations.

The mission of Naval Station Norfolk is

> ...to provide, as appropriate, logistic support for the Operating Forces of the Navy, and for dependent activities and other commands as assigned. ...The Port Services Officer (also known as the Port Operations Officer) is responsible to the Naval Station Commanding Officer for the performance of the port services functions. ...For ships (units) under naval control, the port service's functions include the assignment of berths and anchorages; the use of piers, landing sites, pilots; coordination of logistic requests for supplies, fuel, medical services, communications, hazardous material handling and other services.... (Fleet Guide, 1986, p. 5-3)

The Norfolk Naval Station consists of 15 piers, depicted in Figure 1, which exhibit different physical characteristics and services. Typically, the average number of ships in port is 50 with the highest port load peaking at 74 during the Christmas holiday. These vessels usually rely on shore power rather than on their own power. (Papworth, 1988) Shore power

and other facilities permit ships to operate and test combat systems and other mission capabilities while in port (COMNAVSURFLANT, 1987). The increasing number of ships homeported at Norfolk (presently 118), along with unique requirements by ships and lengthy pier maintenance projects, combine to make pier scheduling an extremely difficult task requiring complex planning (COMNAVSTANORVA, 1987).

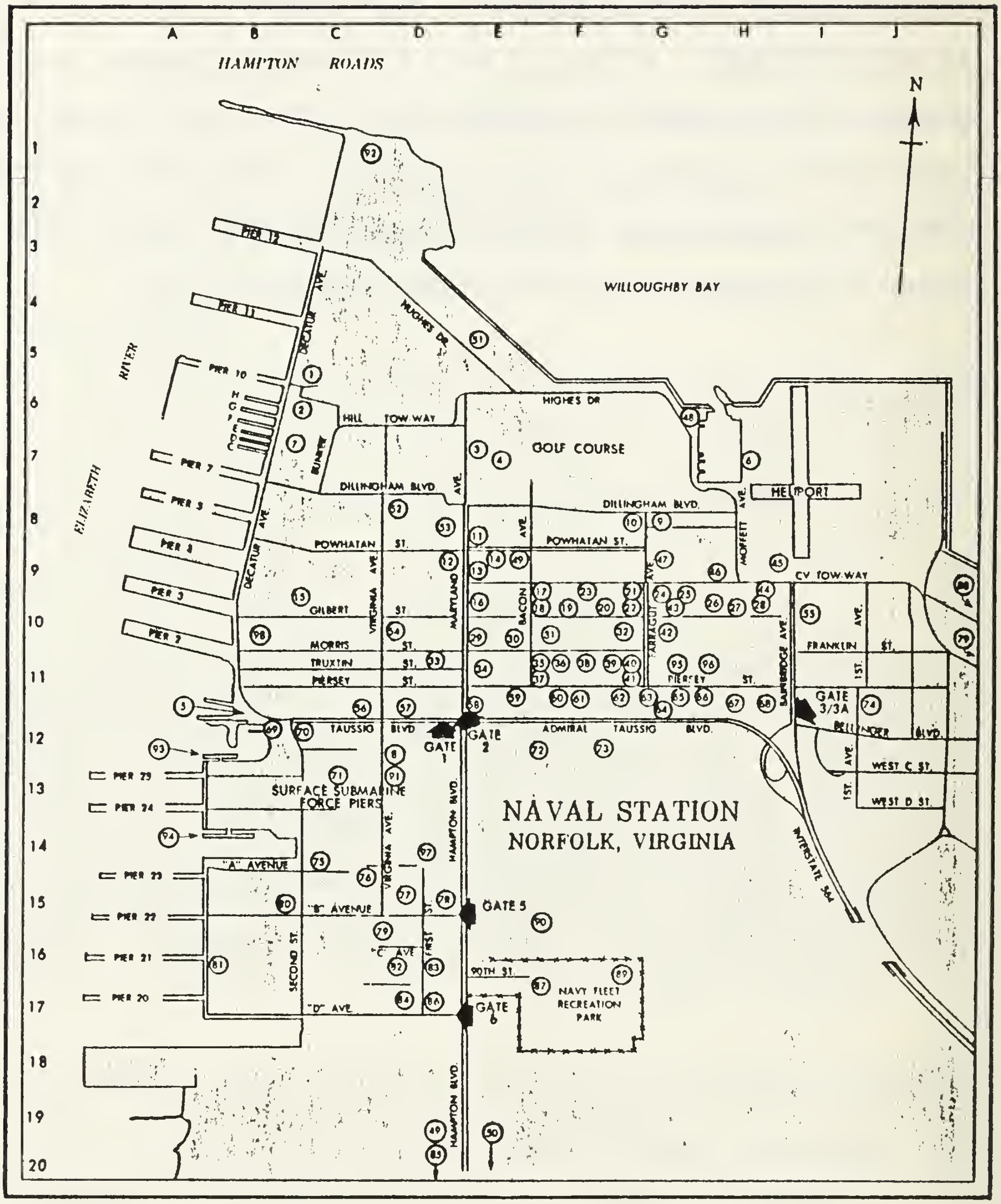


Figure 1. Naval Station Norfolk Piers
Piers have different lengths, water depths, crane services, and power, etc. available.

B. CURRENT PROCEDURES

The Naval Station Norfolk ship berthing plans are manually prepared by the schedulers with the aid of pen and paper and a wall-size mock-up of the pier layout with scale-size ship silhouettes. Once informed of which ships are scheduled to be in port for the next week, the scheduler first determines which berths can physically accommodate each ship.

The berth scheduling rationale is based on the following primary criteria:

1. The ship's length must be less than the length of the pier;
2. The pier-side depth must be five feet greater than the ship's draft to allow for tidal change as well as propeller wash and engineering plant requirements;
3. The ship's beam plus fender system must extend less than the distance between the berth and the next closest pier or berthed ship plus room to allow a ship to maneuver;
4. The berth should provide at least the minimum required number of shore power cables (COMNAVSURFLANT, 1987).

After the physically feasible berths are identified for each ship, the scheduler then considers a secondary set of guidelines specific to Norfolk listed in Appendix A. Every port has an analogous set of local berthing criteria.

At this point, scheduling becomes difficult. The scheduler assigns each ship to a feasible berth and tries to maximize the proportion of requested services and minimize the number of berth shifts required to accommodate these

requests over time. This berth plan is the initial input to a key planning event, the berthing conference.

Once a week, a berthing conference is held at port operations and attended by representatives from squadrons, groups, type commanders, Military Sealift Command, Norfolk Supply Center, Public Works Center (PWC, utilities and crane scheduler), Readiness Support Group and Port Operations (scheduler, chief pilot, ordnance officer, dockmaster and policy maker). The squadrons all represent their ships' requests for docking and undocking times, as well as for particular berth assignments. PWC advertises feasible pier utility services. The pilot assigns move times for ships constrained by tide. Compromises are worked out and the Port Operations Officer makes final decisions. (Papworth, 1988)

The final berthing plan resulting from the berthing conference is used as the start of the following week's schedule. Coordination among all these participants is vital. Changes in the announced plan are inevitable--the schedule often changes hourly. The sheer frequency of revisions makes a strong case for the use of a computerized, optimizing berthing plan. The consequence of oversights is delay, and delays cost time and money.

II. AN OPTIMIZING BERTHING MODEL

The goal is to create an optimal berth plan, at a daily level of detail, for all ships scheduled to be in port during the prospective planning horizon (say, a week). As demonstrated in Chapter I, the berthing requirements are well defined. This chapter explains the basic model developed to satisfy these requirements and produce optimal berth schedules.

The situation calls for a set of discrete ship-to-berth assignments, with limitations on feasible assignments. These limitations (on length, draft, power cables, and so forth) are easily expressed as linear functions of ship-to-berth assignment variables. This suggests a linear integer program.

A. LINEAR INTEGER PROGRAM MODEL FORMULATION

Indices:

$i = 1,\ldots,I$	individual ships
$j = 1,\ldots,I$	individual ships (alternate index)
$p = 1,\ldots,P$	piers
$b = 1,\ldots,B$	berths
$n = 1,\ldots,N$	nesting position (1=pierside,...,N-1= next-to-last position)
$t = 0,\ldots,T$	day (t=0 indicates current day)
$k = 1,\ldots,K$	basin
$q = 1,\ldots,Q$	services

$m = 1,\ldots,M$	ship characteristics (draft, length,...)
$z = 1,\ldots,Z$	pier characteristics (depth, length,...)

For simplicity of presentation, it is implicitly understood in the following that only permissible combinations of indices are used.

Given and Derived Data:

D_{pk}	1 if pier p belongs to basin k; 0 otherwise
L_p	length of pier p + allowable overextension of ships during high port loading
l_i	length of ship i + minimum distance between adjacent ships (bow/stern, stern/stern, seawall/ship)
E_p	number of power cables available at pier p
e_i	minimum number of power cables required by ship i
W_k	width of basin k - tug maneuvering room
w_i	beam of ship i + fendering
s_i	N if ship i cannot physically nest; 1 otherwise
u_i	1 if ship i can berth ships outboard; 0 otherwise
F_{ip}	1 if fendering and superstructure on pier p is compatible with ship i; 0 otherwise
SD_{im}	characteristic m for ship i
PD_{pz}	characteristic z for pier p
R_n	reward for nest position
LQ_{iq}	ship i priority for requested service q

A_{qp}	1 if Pier service q is available on pier p; 0 otherwise
DR	safety distance between ship draft and water depth
C_{ipbnt}	1 if $t \geq 1$ and ship i can physically fit in specified berth b at pier p, at nesting position n, and is scheduled to be in port on day t; 0 otherwise, in particular when s_i = N and $n \geq 2$

In order to help the human scheduler, rather than (foolishly) try to replace him, extensive user-friendly facilities should be provided to allow manual assignment of a ship to a specific berth, subset of piers/berths, or nesting position. These coercions are simulated in the prototypic implementation via input of derived compatibility data, C_{ipbnt}. This allows the scheduler to restrict any or all permitted indices for a ship, i.e., a specific berth, group of berths/piers, and/or nesting position for a specific ship during any or all days the vessel is scheduled to be in port. When the user identifies specific requests, all other C_{ipbnt} are automatically set to zero, thus ensuring the ship will be berthed only as specified by the scheduler.

A ship may be assigned to one of the specified berths at a pier as long as all of the primary berthing conditions (1)-(5) are satisfied. If these primary berthing criteria are violated for every pier associated with each specified berth, the ship can not berth and the problem is deemed infeasible.

$$SD_{i,draft} \leq PD_{p,depth} - DR \qquad (1)$$

$$SD_{i,length} \leq PD_{p,pierlength} \qquad (2)$$

$$SD_{i,arrive} \leq t \qquad (3)$$

$$SD_{i,depart} \geq t \qquad (4)$$

$$F_{ip} = 0 \qquad (5)$$

Condition (1) ensures the pier depth is deep enough for the ship's draft plus safety distance. Condition (2) berths a ship only if its length does not extend past the pier. For a ship to be considered compatible, it must be scheduled to be in port during the day considered as ensured by conditions (3) and (4). Condition (5) does not allow a ship to be assigned a berth where it would have a fendering or superstructure interference.

The objective is the "goodness" of any given feasible berthing plan. The problem is greatly simplified if this benefit can be expressed as an additive, separable linear function of individual ship-to-berth assignments. To provide such an objective function, individual ship service requests are prioritized among and between ship classes: larger ships such as aircraft carriers are authorized higher priorities for services than destroyers or frigates. The benefit is expressed as a function based on this ship priority for services, pending inspections, deployments, whether the pier

offers any or all of the requested services and how far into the future the decision will be committed.

Recognizing the time value of information and uncertainty, an exponential function discounts the preference awarded to a ship desiring a berth in the future vice a ship requesting it today.

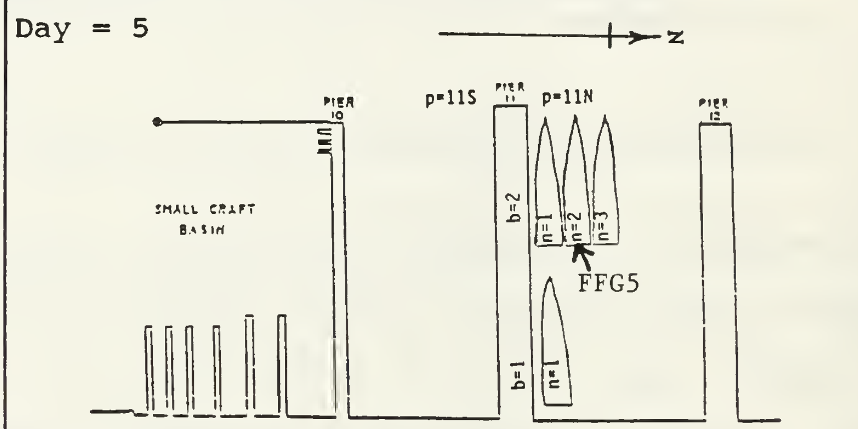
BN_{ipbnt} benefit from berthing ship i, at pier p, in berth b, at nesting position n, on day t; derived only if $C_{ipbnt} = 1$, and defined as follows:

$$BN_{ipbnt} = e^{\left(\frac{-t}{T}\right)} \left[\sum_{q} LQ_{iq} A_{qp} + SD_{iinspect} + SD_{ideploy} \right] + R_n.$$

The benefit of a potential assignment is thus calculated by summing term-by-term the pairwise products of the weighted ship requests (LQ) with the vector (A) which identifies services available at each pier. This is an indication of how well each berth satisfies a ship's needs. The inspection and deployment (SD) factors are then added to the weighted ship requests; this allows a ship with an upcoming inspection or deployment to be ranked higher than other ships of the same type. The updated weight is multiplied by an exponential term to give a greater consideration to ships requesting services today than ships scheduled to be in port in the future. Lastly, a reward (R) based on nesting position is added to yield the final benefit for assigning the ship to a specific berth. This final nesting position reward encourages the model to berth ships pierside.

Variables:

X_{ipbnt} A binary variable specifying if ship i is to be berthed at pier p, in berth b, at nesting position n, on day t. In the implementation, the variable, X_{ipbnt}, is included in the model only when the corresponding assignment satisfies the feasibility conditions 1-5. To take into account the fact that the berthing of ships is an ongoing process, t=0 indicates a ship's current position. Figure 2 illustrates the meaning of each index graphically.



Ship FFG5 is berthed at pier 11N, berth 2, nesting position 2 on day 5;
$X_{FFG5,11N,2,2,5}=1$

Figure 2. Ship Berthing Index Use Diagram

Z_{ipbnt} indicates if ship i shifted to pier p, in berth b, at nesting position n, on day t. This variable is generated only if the ship was berthed on day t-1.

Formulation: Maximize $$\sum_{ipbnt} BN_{ipbnt} X_{ipbnt} - \sum_{ipbnt} SD_{i,penalty} Z_{ipbnt}$$

Subject to:

$$\sum_{ib} l_i X_{ipb1t} \leq L_p \qquad p,t \in (PxT) \tag{6}$$

$$\sum_{ibn} e_i X_{ipbnt} \leq E_p \qquad p,t \in (PxT) \tag{7}$$

$$\sum_{i} l_i X_{ipbnt} \geq \sum_{i} l_i X_{ipb(n+1)t} \qquad p,b,n,t \in (PxBx(N-1)xT) \tag{8}$$

$$\sum_{pbn} X_{ipbnt} = 1 \qquad i,t \in (IxT) \tag{9}$$

$$\sum_{i} X_{ipbnt} \leq 1 \qquad p,b,n,t \in (PxBxNxT) \tag{10}$$

$$\sum_{in} S_i X_{ipbnt} \leq N \qquad p,b,t \in (PxBxT) \tag{11}$$

$$(N-n)X_{ipbnt} + \sum_{j \neq i} X_{ipb(n+1)t} + \sum_{j \neq i} X_{ipb(n+2)t} \leq N-n \tag{12}$$

$$i,p,b,n,t \in (I|(u_i = 1)xPxBx(N-1)xT)$$

$$\sum_{ipn} W_i D_{pk} X_{ipbnt} \leq W_k \qquad k,b,t \in (KxBxT \in (SD_{i,arrive} < t)) \tag{13}$$

$$X_{ipbnt} - X_{ipbn(t-1)} - Z_{ipbnt} \leq 0 \qquad i,p,b,n,t \in (IxPxBxNxT) \tag{14}$$

$$X_{ipbnt} \in \{0,1\} \qquad i,p,b,n,t \in (IxPxBxNxT) \tag{15}$$

$$Z_{ipbnt} \geq 0 \qquad i,p,b,n,t \in (IxPxBxNxT) \tag{16}$$

In the above formulation, the objective function is to maximize the ship-to-berth assignment benefits less a berth shift penalty. This penalty decreases the total benefit of the plan each time a vessel is required to move to a different berth or nesting position from day to day in order to receive required services at a new berth or to free its current berth for another ship. Since the formulation encompasses the entire planning horizon, the optimal plan takes into account the arrival on any day of new ships and their required services. Initial ship positions are treated as arrivals on day 0.

Constraints (6) require that the total length of ships berthed at pier p and nested inboard are less than the length of the pier plus allowable extension. Constraints (7) ensure that each pier has sufficient number of power cables to support ships berthed alongside. Constraints (8) allow ships to be nested outboard another vessel only if its length is less than or equal to that of the inboard vessel. Constraints (9) ensure each ship is berthed at only one slip when scheduled to be in port while constraints (10) allow only one ship per berthing position. Constraints (11) ensure specific ships do not nest and constraints (12) preclude berthing outboard of incompatible ships. Constraints (13)

provide room for a tug to maneuver among berthed ships in each basin. Berth shifting is calculated with constraints (14). Conditions (15) ensure the assignment variable is binary while (16) requires the berth shift variable to be nonnegative.

III. SHIP BERTHING PLAN EXAMPLE PROBLEM

A prototype model has been evaluated using a GAMS generator (Brooke, Kendrick, and Meeraus, 1988) and MPSX solver (IBM, 1972). The model has been tested using an example with seventeen ships, eight piers (see Figure 3), and a six-day planning horizon.

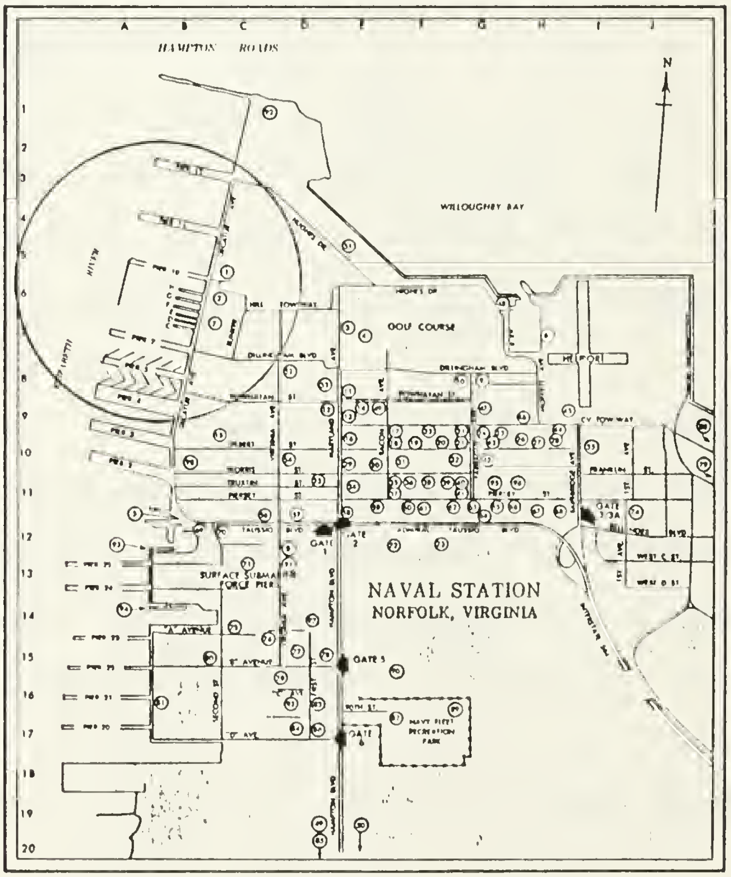


Figure 3. Norfolk Naval Station
Piers 4S, 7, 10, 11, and 12 are scheduled in the example problem.

This example incorporates a wide variety of ship types: carrier, frigate, destroyer, cruiser, oiler and battleship.

The physical characteristics input for each ship include: length, draft, beam, arrival date, departure date, number of shore power (PWR) cables required, whether the ship can nest (SHP) or allow ships outboard (NOOUT). Upcoming inspections or deployments are identified along with the penalty incurred if a berth shift is required (COSTSHF). Table 1 displays a sample of the GAMS data input for the seventeen ship example problem.

TABLE 1.

EXAMPLE PROBLEM SHIP CHARACTERISTICS

SHIPDATA(I,SDATA) LIST OF SHIPS AND CHARACTERISTICS

	LENGTH	DRAFT	BEAM	ARRIVE	DEPART	SHIPPWR	INSPECT	DEPLOY	SHP	COSTSHF
AFS2	581	24	79	5	5	4				400
AOR4	659	33.3	96	3	5	3				500
DDG4	437	20	47	2	5	3				300
DDG6	437	20	47	1	5	3				300
LHA4	840	26	106	2	5	14			1	400
BB61	887	38	108	1	2	6				500
BB61a	887	38	108	5	5	6				500
CVN71	1300	37	134	1	5	8			1	1000
CV67	1300	35.9	130	1	5	24		200	1	1000
CV66	1300	37	130	1	3	24		200	1	1000
CG27	547	28.8	54.8	1	4	4				350
CG30	547	28.8	54.8	2	5	4				350
CG34	547	28.8	54.8	4	5	4				350
CG48	567	33	55	1	3	6	100			350
CG51	566	31	55	1	2	6				350
FFG5	414	24.2	44.2	1	4	2		100		300
TAF8	524	22	72	1	2	2				400
TAO189	678	34.5	97.5	2	4	4				400;

To identify any particular ship or ship type, refer to Jane's Fighting Ships, 1988. Each pier is characterized in Table 2 by its length, depth and shore power available: each basin width is identified along with the piers that form the basin.

TABLE 2.
PIER CHARACTERISTICS

PIERDATA(P,PDATA) LIST OF PIERS AND CHARACTERISTICS

	PIERL	DEPTH	POWER
12N	1300	50	24
12S	1300	50	24
11N	1397	50	24
11S	1397	50	24
10N	1300	38	56
7N	1350	45	24
7S	1350	45	21
4S	1347	40	24;

The services available pierside include: diesel fuel (DFM), JP5 fuel, Military Sealift Command (MSC), Stores, 140T crane, DESRON2 (DRON2) and COMDESGRU8 (CDG8) sponsorship, and ordnance handling certification. Table 3 shows the pier and service availability GAMS input used in the sample problem.

TABLE 3.

EXAMPLE PROBLEM PIER/SERVICE AVAILABILITY

AVAIL(P,J) LIST OF PIERS WITH SERVICES OFFERED

	DFM	JP5	MSC	STR	140T	4160V	DRON2	ORDN	CD68	TEND
12N	1	1				1		1		
12S	1	1				1		1		
11N						1		1		
11S						1		1		
10N									1	
7N	1	1						1		1
7S	1							1		
4S	1	1	1	1	1;					

The maximum "weights" authorized for ship types to request services are listed in Table 4.

TABLE 4.
MAXIMUM WEIGHTS AUTHORIZED FOR SHIP/SERVICE REQUESTS

SHIPS	WEIGHTS
CV/CVN	1000
BB	900
LHA/AOE/AOR/AD/AO	800
TAO/TAF/AFS	700
LPH/LPD/LST	600
CG/CGN	500
DD/DDG	400
FF/FFG	300
ARS/MSO	200

The maximum weight limits are used to edit the priority for services requested by a ship.

The weighted values assigned to each ship for requested services are easily identified in the GAMS data matrix utilized in the example problem as seen in Table 5.

TABLE 5.

EXAMPLE LOGREQ PRIORITIES FOR SHIP SERVICES

LOGREQ(I,J) WEIGHTED SHIP TO SERVICES REQUIREMENTS

	DFM	JP5	MSC	STR	140T	4160V	DRON2	ORDN	CD68	TEND
AFS2				600	600					
AOR4	750	750								
LHA4										
DDG4										
DDG6										
BB61										
BB61a	600									
CVN71		900				999				
CV67		900								
CV66		900								
CG27									400	
CG30									400	
CG34									400	
CG48									400	
CG51									400	
FFG5	200									
TAF8			700	700	400					
TAO189			700;							

For instance, BB61a indicates a second inport period for BB61 during the planning horizon; AOR4 has an assigned weight of 750 for the requested services of DFM and JP5.

The remaining physical characteristics for all ships, piers and basins essential to the problem are given in Appendix B. The resulting integer program is generated by GAMS and solved using the MPSX solver. The final GAMS output berthing plan is displayed in Table 6 and illustrated in Figures 4 through 9. Each daily berth plan is printed to show all ships scheduled to be in port and their assigned berth. The dashed silhouettes in Figures 4 through 9 indicate a ship departure and the arrows identify berth shifts.

TABLE 6.

GAMS OUTPUT FOR FINAL BERTHING PLAN

---- 380 PARAMETER DAY = 1.000 COUNTER OF DAY

---- 380 PARAMETER SOL

	12N.2.INBD	12S.1.INBD	11N.2.INBD	10N.1.INBD	10N.1.OUTBD	10N.2.INBD	7N.1.INBD	7S.1.INBD	7S.2.INBD	4S.2.INBD
CVN71	1.0									
CV67			1.0							
CV66		1.0								
CG27					1.0					
CG48						1.0				
CG51				1.0						
FFG5							1.0			
TAF8										1.0
BB61								1.0		
DDG6									1.0	

```
----    380 PARAMETER DAY         *       2.000 COUNTER OF DAY

----    380 PARAMETER SDL
```

	12N.2.INBD	12S.1.INBD	11N.2.INBD	11S.1.INBD	11S.2.INBD	10N.1.INBD	10N.1.OUTBD	10N.2.INBD	10N.2.OUTBD	7N.1.INBD
CVN71	1.0									
CV67			1.0							
CV66		1.0								
CG27							1.0			
CG30						1.0				
CG48								1.0		
CG51									1.0	
FFG5										1.0
LHA4					1.0					
DDG4				1.0						

+	7S.1.INBD	7S.2.INBD	4S.1.INBD	4S.2.INBD
TAFB				1.0
TADIB9			1.0	
8B61	1.0			
DDG6		1.0		

```
----    3B0 PARAMETER DAY         *       3.000 COUNTER OF DAY

----    3B0 PARAMETER SOL
```

	12N.2.INBD	12S.1.INBD	11N.2.INBD	11S.1.INBD	11S.2.INBD	10N.1.INBD	10N.1.OUTBD	10N.2.INBD	7N.1.INBD	7N.2.INBD
ADR4										1.0
CVN71	1.0									
CV67			1.0							
CV66		1.0								
CG27							1.0			
CG30						1.0				
CG48								1.0		
FFG5									1.0	
LHA4					1.0					
DDG4				1.0						

+	7S.2.INBD	4S.1.INBD
TAD189		1.0
DDG6	1.0	

---- 380 PARAMETER DAY • 4.000 COUNTER OF DAY

---- 380 PARAMETER SOL

	12N.2.INBD	11N.2.INBD	11S.1.INBD	11S.2.INBD	10N.1.INBD	10N.1.OUTBD	10N.2.INBD	7N.1.INBD	7N.2.INBD	7S.2.INBD
AOR4									1.0	
CVN71	1.0									
CV67		1.0								
CG27						1.0				
CG30					1.0					
FFG5								1.0		
LHA4				1.0						
DDG4			1.0							
DDG6										1.0
CG34							1.0			

	• 4S.1.INBD
TA01B9	1.0

---- 380 PARAMETER DAY • 5.000 COUNTER OF DAY

---- 380 PARAMETER SOL

	12N.2.INBD	12S.2.INBD	11N.2.INBD	11S.1.INBD	11S.2.INBD	10N.1.INBD	10N.2.INBD	7N.2.INBD	7S.2.INBD	4S.2.INBD
AFS2										1.0
AOR4								1.0		
CVN71	1.0									
CV67			1.0							
CG30						1.0				
BB61A		1.0								
LHA4					1.0					
DDG4				1.0						
DDG6									1.0	
CG34							1.0			

Figure 4 shows the position of ships in port at start of the planning horizon.

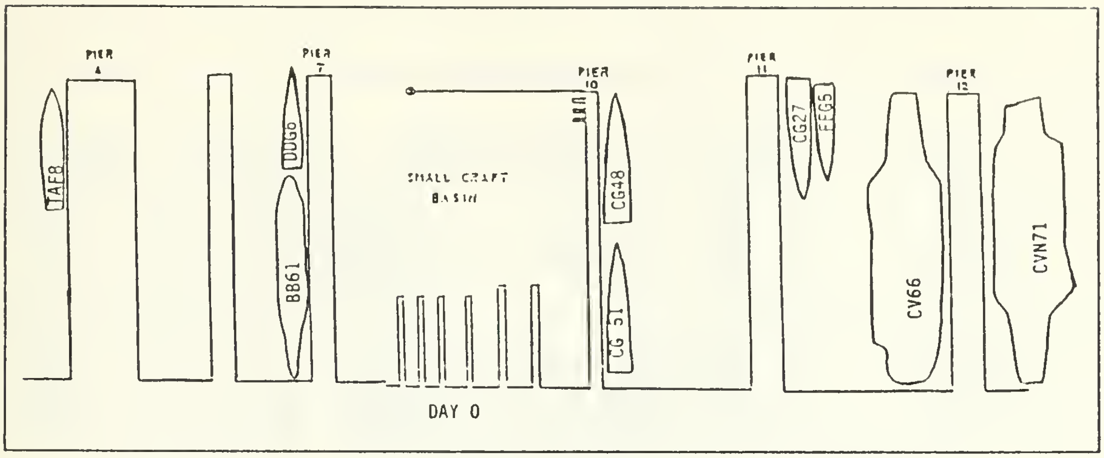


Figure 4. Day 0 Ship Berthing Sample Plan

Figure 5 illustrates that on Day 1 both FFG5 and CG27 are required to berth shift in order to make room for the arrival and berthing of CV67. The slashes outboard CG27 indicate the ship's request for none to berth outboard.

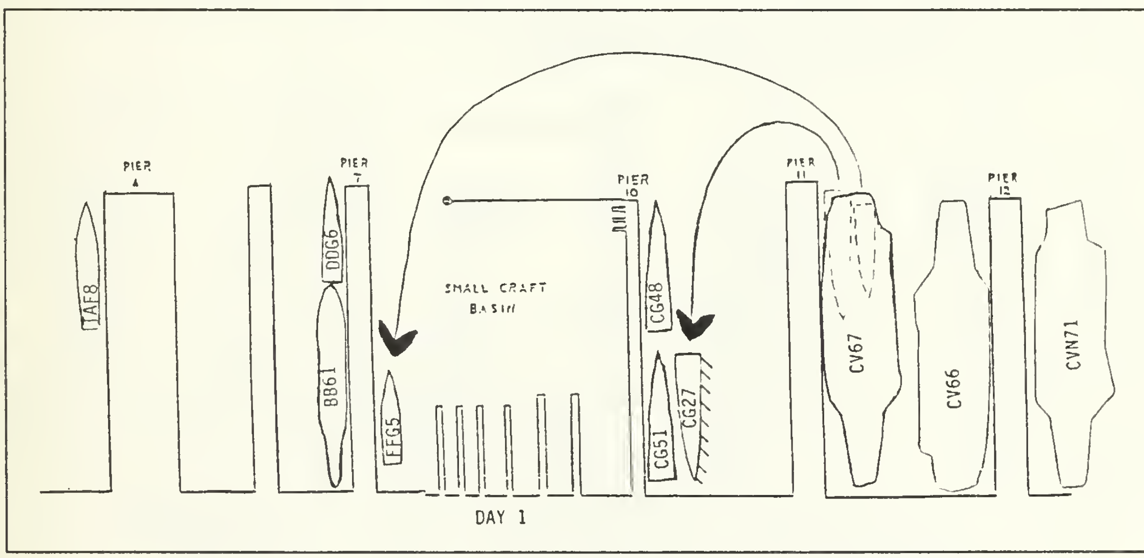


Figure 5. Day 1 Ship Berthing Sample Plan

On Day 2, TAO189, LHA4, DDG4 and CG30 arrive inport. CG51 berth shifts to allow CG30 to berth pierside in accordance with the scheduler's input. These activities are shown in Figure 6.

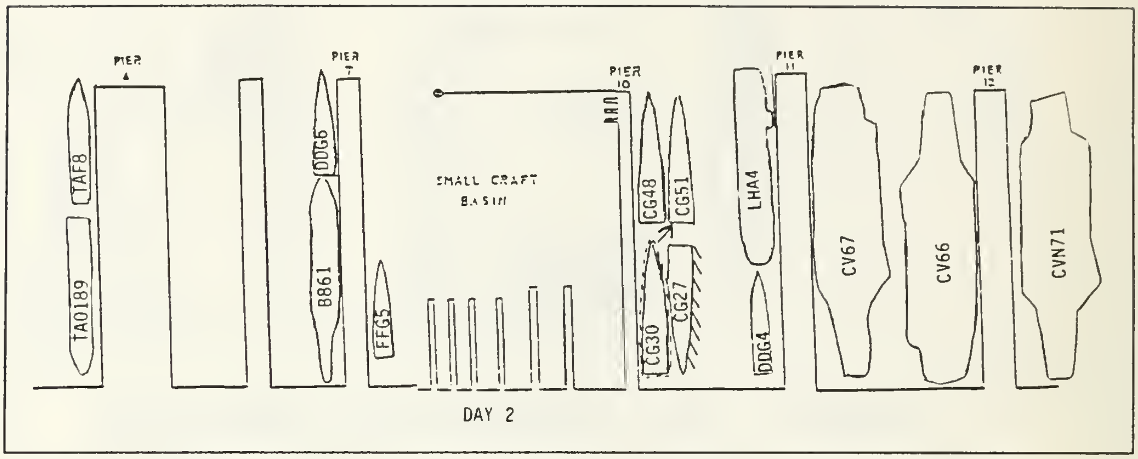


Figure 6. Day 2 Ship Berthing Sample Plan

BB61, CG51, and TAF8 depart and are underway on Day 3 whereas AOR4 arrives in port. When CG51 leaves its pier, CG30 berth shifts to be pierside vice nested out. These events are displayed in Figure 7.

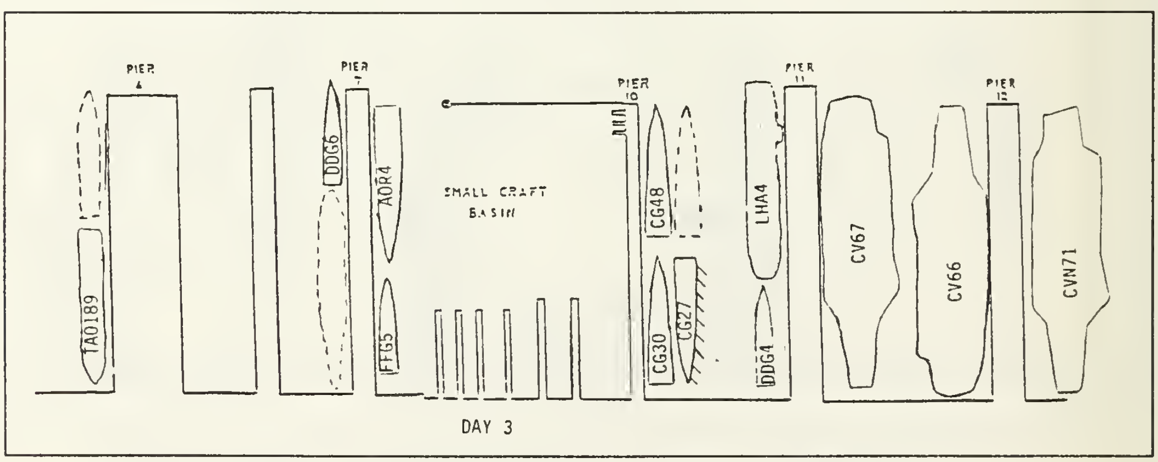


Figure 7. Day 3 Ship Berthing Sample Plan

CG48 and CV66 are underway from Norfolk on Day 4. CG34 arrives at the base and assumes CG48's berth illustrated in Figure 8.

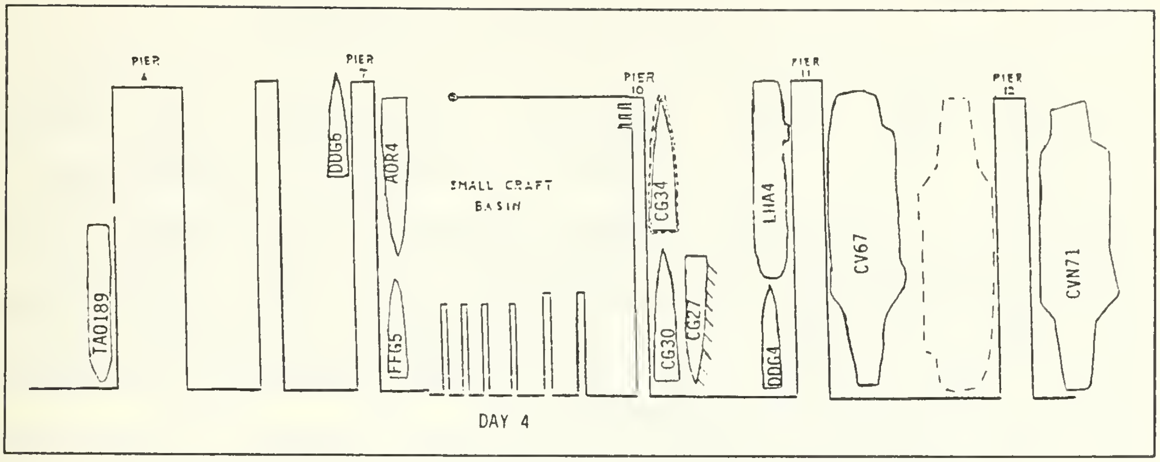


Figure 8. Day 4 Ship Berthing Sample Plan

On Day 5 AFS2 arrives inport and BB61 returns but to a different berth. TAO189, FFG5, and CG27 are underway for sea. Figure 9 identifies these movements.

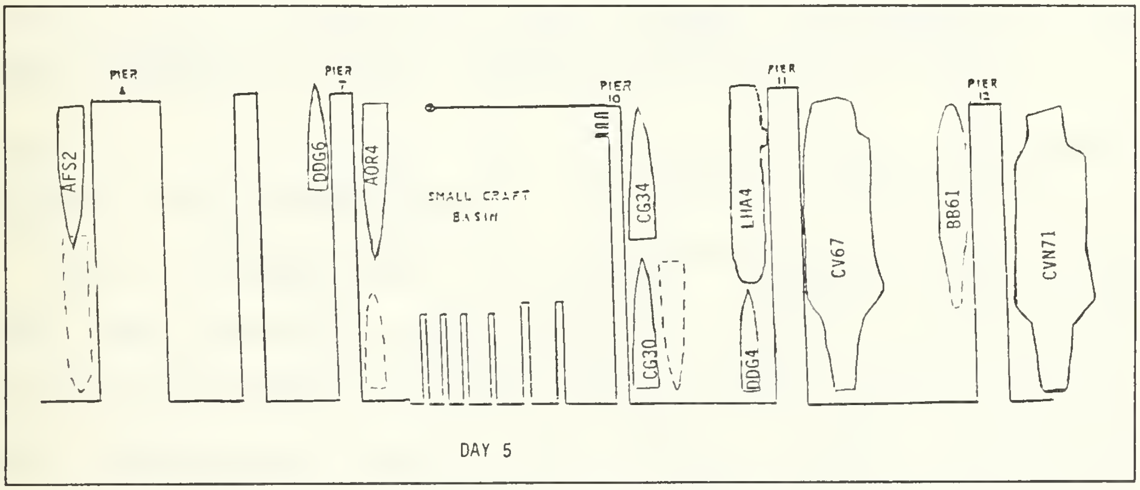


Figure 9. Day 5 Ship Berthing Sample Plan

IV. COMPUTATIONAL EXPERIENCE

GAMS, the General Algebraic Modeling System (Bisschop and Meeraus, 1982), "is designed to make the construction and solution of large and complex mathematical programming models more straightforward for programmers and more comprehensible to users of models." (Brooke, Kendrick, Meeraus, 1988, p. xiii) GAMS has been developed to:

1. Provide a high-level language for the compact representation of large and complex models;
2. Allow changes to be made in model specifications simply and safely;
3. Allow unambiguous statements of algebraic relationships;
4. Permit model descriptions that are independent of solution algorithms. (Brooke, Kendrick, Meeraus, 1988, p.3)

Using GAMS to implement the prototypic ship berthing model enabled experimentation and easy changes to both the model and its data. However, when analyzing GAMS model results, the user must be very careful to keep the underlying mathematical model in mind: it is very easy to forget about mathematical programming theory and just concentrate on the rather hypnotic allure of powerful GAMS statements. This can (and did) confound verification (debugging) and validation.

The example ship berthing plan problem was originally run using GAMS/MINOS (Murtagh and Saunders, 1983) to debug the model. Unfortunately, MINOS has no integer capabilities.

Since the linear programming relaxation of the problem did not naturally solve with integer values for the binary variables, the FORTRAN-based mixed-integer programming solver XMP/ZOOM was introduced. (Marsten, 1981) and (Singhal, Marsten and Morin, 1987)

The ZOOM solver is "intended for medium-sized problems with no special structure and up to about 200 zero/one variables." (Brooke, Kendrick, Meeraus, 1988, p. 225) Zoom occasionally obtains respectable integer solutions, but only after a long series of experiments adjusting the ZOOM parameters and options. ZOOM consumes enormous computer resources in these trial-and-error experiments. Many shortfalls of the ZOOM solver have been identified and referred back to the developer, Marsten, via Meeraus. ZOOM can not even solve some trivial test problems due to several apparent severe bugs and has therefore been deemed inefficient and unreliable.

With the assistance of Professor Terry Harrison of the Pennsylvania State University, an electronic mail connection via IBM-BITNET has been established permitting the GAMS model to be transported to and solved on the IBM 3090-400 at PENN State using GAMS/MPSX (IBM, 1978). GAMS/MPSX worked, requiring 70 IBM 3090-400 processing seconds and 7,143 iterations to solve the example model with 1,779 constraints, 2,864 variables, 1,512 binary variables and 16,453 non-zero coefficients.

Motivated by these experiences, Professor Harrison is preparing a GAMS/X-System (Brown and Graves, 1975) interface, which he and Brown will test on problems including such as that reported here. The goal is to show that the port scheduling model can be solved quickly and inexpensively at realistic scale on a modest computer (Bausch and Brown, 1988). This is important, because the full-scale Norfolk berth scheduling problem will require some advanced optimization techniques not yet available via GAMS. To see this, consider that with 24 piers, 144 berths, and 74 ships inport an average of five days over a seven-day berthing plan, up to 120,107 constraints and 53,280 binary variables may be required.

The formidable size of the hypothetical port scheduling model problems is mitigated by numerous restrictions on permissible realistic combinations of indices (berths, ships, services, etc.). The dollar operator feature in GAMS "provides powerful and concise exception-handling capability." Explicit if-then-else statements constructed within an equation or assignment makes a program more manageable by decreasing the number of equations and variables generated. (Brooke, Kendrick, Meeraus, 1988, p.72)

The entire GAMS/MPSX input listing for the example berthing problem is in Appendix B.

GAMS is a powerful tool, but expensive to use in terms of computer resources. The example model requires 30 IBM 3090-

400 seconds just to generate the input for an optimizer. After solution, the simple report writing takes 4.5 seconds. By contrast, models of equivalent size and complexity are generated in a second, or so, by use of customized problem generators written in general-purpose compiled languages (e.g., FORTRAN). Such old-fashioned generators take longer to write and debug than GAMS, and are less easy to modify, but they generate with enormously improved efficiency. Given that the port schedulers will not likely have an IBM 3090 super computer available soon, or be willing to wait hours for each solution, it seems likely that a more conventional, old-fashioned approach will be called for.

V. CONCLUSIONS

Optimization-based berth scheduling is feasible and effective. The prototype introduced and developed here gives compelling evidence that a computer-based model can express the berthing problem concisely in easy-to-understand displays, and automatically produces berthing plans capturing an enormous amount of the realism and detail that make such scheduling a challenging manual chore. Better yet, the method developed here encourages human interaction.

In the context of the proposed model, extensive user-friendly facilities can be accommodated to allow a port operations scheduler to manually assign a ship to a specific berth, subset of piers/berths or nesting position. The optimization model then completes the tedious details of the berth plan. Thus, the port operations scheduler can naturally express any "human judgement" issues and the optimization assures that high-quality berth plans are easily and quickly produced.

This optimization program would also give the scheduler the flexibility to evaluate alternate "what if" berthing plans. In this role, quick-response identification of upcoming infeasibilities may be as useful as comparative evaluations of the relative merit of alternate plans. There is no current manual analog for this capability, nor is it likely that the manual time and effort will be available to

devote to much more than cursory analysis of schedule changes.

This optimal berthing plan model could easily be adapted for other naval bases and include submarines.

Bases and Stations Information System (BASIS) is a new data base management system currently being installed for prototype tests at Naval Station, Norfolk. BASIS is planned for future use by all U.S. Naval Stations and Bases world-wide. BASIS is "a computer-based network developed to fulfill the command staff's need for timely and accurate information concerning base/station activities." (NPRDC, 1988, p. vii)

The Port Services module of BASIS is designed to support management in the complete and efficient supervision of Port Services functions by maintaining data that can be used in assessing current and future Port Services needs. The system "operates in an on-line environment utilizing Video Display Terminals that allow for interactive processing of data via add, change, delete and display functions." (NARDAC, 1988, p. iii)

The Port Services module is capable of handling waterfront functions such as current and projected berthing plans, maintenance schedules, waterfront status, ship and pier characteristic data, ship schedules, pier maintenance

projects, and a variety of statistical data. (NARDAC, 1988, p. iii)

An optimization-based berth scheduling module can be embedded in BASIS, providing a powerful decision aid to port operations management. Given the design specifications of BASIS, an optimal berthing model should be able to retrieve the information it needs. Following optimization, the video display features of BASIS would be invaluable in expressing the current and planned port activities. The pictorial display of a ship berthing plan is very useful and easier for the scheduler to interpret than an assignment table. Thus, the port operations scheduler could produce efficient and current berthing plans.

Port scheduling is crucial to the U.S. Navy. Considering the tempo of schedule changes and the meticulous detail which preparation of every schedule must consider, a manual scheduler is hard-pressed to weigh myriad alternatives and fine-tune every alteration. It is inevitable that oversights will lead to delays. If an automatic, optimization-based decision support system prevents unnecessary delays or berth shifts, then such a system clearly contributes to the readiness of the fleet.

APPENDIX A

NAVAL STATION NORFOLK BERTH SCHEDULING GUIDELINES

1. Due to pier superstructure, the following ship types can not berth at these prohibited locations:

SHIP TYPE	PROHIBITED LOCATIONS
LSD,LPD	PIER 4 berth 5 and 6
CV/CVN	PIER 2,3,4,10

2. The fendering system limits the ship types certain piers are or can be configured for. All other ship types may go to any berth provided it is physically feasible and shore power is available.

SHIP TYPE	COMPATIBLE PIERS
BB	all except 10
LHA	5,7,10,11,12,25N
LPH	2,5,7,11,12
LPD	2,3,4,5,7,10-5,11,12
CV/CVN	7N,11,12

3. Ships would like to be berthed at piers that their respective squadrons "sponsor".

PIER	SPONSOR SQUADRON
20	SERVGRU4
21	DESRON 2
24,25	DESRON 10
10,25	CRUDESGRU 8

4. During high port loading, ships berthed bow out may extend up to 20 feet beyond the end of the pier.

5. Maintain a distance of 50 feet between ships berthed bow-to-bow, bow-to-stern, stern-to-bow, and 25-50 feet between a ship's bow-to-stern and a seawall.

6. The larger the ship, the higher its priority should be in receiving services.

7. Do NOT nest CV, CVN, LHA, LPH and LPDs due to their hull structure.

8. An outboard ship's length must be less than or equal to the inboard ship's length. This minimizes the stress on mooring lines. However, during high port loading, the outboard ship may be up to 20 feet longer.

9. Preferably, berth ships in "UPKEEP" near a tender or SHip Intermediate Maintenance Facility (SIMA), responsible for repairs.

10. Certain services are rendered only at specific piers: e.g., refueling pier side, ordnance transfer, major stores loading, collimation (piers 5, 7, 24, 25; berths 1 and 2), sonar testing (bow out, end of pier), and cranes.

11. The maximum number of ships nested is usually two but may go up to four. This is primarily due to shore power limitations.

12. If LHAs require lowering their ramp, they must do so on piers 5,7,11 or 12. (The drive-on and -off ramp is used to load vehicles.)

13. Certain ships MUST go to specific berths. (e.g., USS Mount Whitney, Pier 25-1)

14. Ships preparing for deployment and inspections have a higher priority for services than others of the same ship type.

15. Two ships of certain classes may berth Chinese (bow-to-stern). (Spruance, Oiler, BB, Ticonderoga, Yorktown, DDG, FF) This is not a major factor but may be a consideration. (This is an infrequent event.)

16. Ships undergoing a Radiation Hazard (RADHAZ) survey must be 200 feet out of range of any line-of-sight shore structure or other ship's superstructure. (This is an infrequent event.)

17. Berth ships (AOE, AO, AOR, AFS) requesting inport underway stream qualification training and tests, underway replenishment standard qualification trials (UNREP SQTS) across from each other in the same basin or across an unobstructed pier. (This is an infrequent event.) See Figure 4.

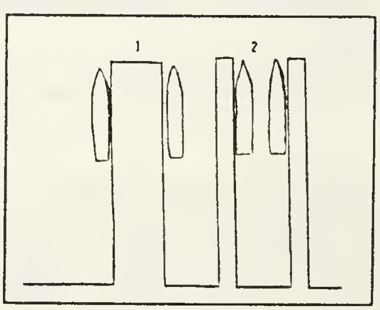


Figure. 4 UNREP SQTTS Berthing Positions

18. SUBRON 6 and 8 are responsible for assigning submarines and tenders to berths on piers 22 and 23. Thus, piers 22 and 23 are removed from our considerations.

19. Phone lines, fresh water, 125psi steam, and collection, holding and transfer (CHT) hook-ups are not scare at the Norfolk Base and are therefore not considered in the model.

APPENDIX B

GAMS INPUT FOR SAMPLE BERTHING PROBLEM

```
$TITLE SHIP SHIP BERTHING - LINEAR PROGRAMMING
$OFFUPPER
$OFFSYMXREF
$OFFSYMLIST
$OFFUELXREF
$ONTEXT

   The model now will assign a ship to a berth during the time period
   the ship is scheduled to be inport.
$OFFTEXT
*------------------------------------------------------------------
*                          INDICES
*------------------------------------------------------------------
 SETS

 I         SHIPS
           /AFS2,AOR4,CVN71,CV67,CV66,CG27,CG30,CG48,CG51,FFG5,TAF8,
                   TAO189, BB61, BB61a,LHA4,DDG4,DDG6, CG34/

 SDATA     SHIP DATA
           /LENGTH,DRAFT,BEAM,ARRIVE,DEPART,SHIPPWR,INSPECT,
                                   DEPLOY,SHP,COSTSHF/

 P         PIERS
           /12N,12S,11N,11S,10N,7N,7S,4S/

 PDATA     PIER DATA
           /PIERL,DEPTH,POWER/

 J         SERVICE
           /DFM,JP5,MSC,STR,140T,4160V,DRON2,ORDN,CD68,TEND/

 T         TIME PERIOD IN JULIAN DAYS
           /D1*D5/

 B         BERTH
           /1,2/

 IO        INBOARD OR OUTBOARD BERTH
           /INBD,OUTBD,OUTBD1/

 BASIN     AREA BETWEEN TWO ADJACENT PIERS
           /BS1,BS2,BS3,BS4,BS5,BS6/;

 ALIAS     (I,IP);
```

```
*-----------------------------------------------------------------
*                    GIVEN  DATA
*-----------------------------------------------------------------

 SCALAR
 ADRAFT     SAFETY DISTANCE BET SHIP AND WATER BOTTOM /5/
 TUGWIDTH   BEAM WIDTH OF A STANDARD TUG /110/
 EXTEND     MAXIMUM DISTANCE SHIPS MAY EXTEND PAST PIER /20/
 BETWEEN    BOW STERN DISTANCE BETWEEN SHIPS AND OR SEAWALL /20/
 FENDER     FENDER DISTANCE BETWEEN NESTED SHIPS AND PIER /10/;

 TABLE

 PIERDATA(P,PDATA)             LIST OF PIERS AND CHARACTERISTICS

          PIERL  DEPTH  POWER
 12N      1300    50     24
 12S      1300    50     24
 11N      1397    50     24
 11S      1397    50     24
 10N      1300    38     56
 7N       1350    45     24
 7S       1350    45     21
 4S       1347    40     24;


 TABLE

 SHIPDATA(I,SDATA)              LIST OF SHIPS AND CHARACTERISTICS

       LENGTH DRAFT BEAM ARRIVE DEPART SHIPPWR INSPECT DEPLOY SHP COSTSHF
 AFS2    581    24     79   5      5      4                          400
 AOR4    659    33.3   96   3      5      3                          500
 DDG4    437    20     47   2      5      3                          300
 DDG6    437    20     47   1      5      3                          300
 LHA4    840    26    106   2      5      14                   1     400
 BB61    887    38    108   1      2      6                          500
 BB61a   887    38    108   5      5      6                          500
 CVN71  1300    37    134   1      5      8                    1    1000
 CV67   1300    35.9  130   1      5      24             200   1    1000
 CV66   1300    37    130   1      3      24             200   1    1000
 CG27    547    28.8  54.8  1      4      4                          350
 CG30    547    28.8  54.8  2      5      4                          350
 CG34    547    28.8  54.8  4      5      4                          350
 CG48    567    33    55    1      3      6       100                350
 CG51    566    31    55    1      2      6                          350
 FFG5    414    24.2  44.2  1      4      2              100         300
 TAF8    524    22    72    1      2      2                          400
 TAO189  678    34.5  97.5  2      4      4                          400;
```

TABLE

AVAIL(P,J) LIST OF PIERS WITH SERVICES OFFERED

	DFM	JP5	MSC	STR	140T	4160V	DRON2	ORDN	CD68	TEND
12N	1	1				1		1		
12S	1	1				1		1		
11N						1		1		
11S						1		1		
10N									1	
7N	1	1						1		1
7S	1							1		
4S	1	1	1	1	1;					

TABLE

LOGREQ(I,J) WEIGHTED SHIP TO SERVICES REQUIREMENTS

	DFM	JP5	MSC	STR	140T	4160V	DRON2	ORDN	CD68	TEND
AFS2				600	600					
AOR4	750	750								
LHA4										
DDG4										
DDG6										
BB61										
BB61a	600									
CVN71		900				999				
CV67		900								
CV66		900								
CG27									400	
CG30									400	
CG34									400	
CG48									400	
CG51									400	
FFG5	200									
TAF8			700	700	400					
TAO189			700;							

TABLE

BELONG(BASIN,P) PIERS BELONGING TO THE SAME BASIN

	12N	12S	11N	11S	10N	7N	7S	4S
BS1	1							
BS2		1	1					
BS3				1	1			
BS4						1		
BS5							1	
BS6								1;

```
TABLE

DESIRE(I,P,B,IO,T)        DESIRE POSITIONS FOR SHIPS BY DAY

                                                      D1  D2  D3  D4  D5
BB61.(7N,7S).(1,2).INBD                               1   1   1   1   1
CVN71.12N.2.INBD                                      1   1   1   1   1
CV66.12S.1.inbd                                       1   1   1   1   1
CV67.(11N,11S).(1,2).INBD                             1   1   1   1   1
CG30.10N.(1,2). INBD                                  1   1   1   1   1
CG34.10N.(1,2).inbd                                   1   1   1   1   1
CG51.10N.(1,2).(INBD,OUTBD)                           1   1   1;


 PARAMETER
 PREV(I,P,B,IO) PREVIOUSLY ASSIGNED SHIPS;

  PREV('FFG5','11N','2','OUTBD')=1;
  PREV('CVN71','12N','2','INBD')=1;
  PREV('CG27','11N','2','INBD')=1;
  PREV('CG48','10N','2','INBD')=1;
  PREV('CG51','10N','1','INBD')=1;
  PREV('TAF8','4S','2','INBD')=1;
  PREV('CV66','12S','1','inbd')=1;
  PREV('DDG6','7S','2','INBD')=1;
  PREV('BB61','7S','1','INBD')=1;

PARAMETER

NOOUT(I)          IDENTIFIES SHIPS THAT CANNOT NEST SHIPS OUTBOARD
    /CG27    1/

REWARD(IO)         REWARD FOR ASSIGNING SHIP INBOARD VICE OUTBOARD

 /INBD             300
  OUTBD            200
  OUTBD1           100/

BWIDTH(BASIN)             WIDTH OF BASIN

    /BS1  365
     BS2  765
     BS3  700
     BS4  283
     BS5  365
     BS6  220/
```

```
FENSUP(I,P) FENDER AND SUPERSTRUCTURE RESTRICTION OR SUBJECTIVE LIMITS

  / CVN71.10N       -1
    CVN71.7N        -1
    CV66.10N        -1
    CV67.10N        -1
    LHA4.4S         -1/;


*---------------------------------------------------------------
*                   DERIVED DATA
*---------------------------------------------------------------

SCALAR

DAY         COUNTER OF DAY  /1/;

PARAMETER

INPORT(I)
BENEFIT(I,P,B,IO,T)
CHKSPEC(I,T)
COMPAT(I,P,B,IO,T)  COMPATABLE SHIP-TO-PIER ASSIGNMENTS;

  SHIPDATA(I,'SHP') = SHIPDATA(I,'SHP')*2+1;

  CHKSPEC(I,T) = SUM( (P,B,IO), DESIRE(I,P,B,IO,T)) ;
  COMPAT(I,P,B,IO,T)=0;

  COMPAT(I,P,B,IO,T) = 1
   $ (    (SHIPDATA(I,'DRAFT')    LE  (PIERDATA(P,'DEPTH')-ADRAFT))
      AND (SHIPDATA(I,'LENGTH')   LE  PIERDATA(P,'PIERL'))
      AND (SHIPDATA(I,'DEPART')   GE  ORD(T))
      AND (SHIPDATA(I,'ARRIVE')   LE  ORD(T))
      AND (FENSUP(I,P)            NE  -1)  );

  COMPAT(I,P,B,IO,T)$(CHKSPEC(I,T) GT 0) = 1
         $( (DESIRE(I,P,B,IO,T) EQ 1)
                       AND (COMPAT(I,P,B,IO,T) EQ 1));

 COMPAT(I,P,B,'OUTBD',T)$(SHIPDATA(I,'SHP') EQ 3)=0;

 COMPAT(I,P,B,'OUTBD1',T)$(SHIPDATA(I,'SHP') EQ 3)=0;

  BENEFIT (I,P,B,IO,T)$(COMPAT(I,P,B,IO,T) GE 1) = EXP(-(ORD(T)-1)/7) *
    ( SUM(J, LOGREQ(I,J)*AVAIL(P,J))
                          + SHIPDATA(I,'INSPECT')
                + SHIPDATA(I,'DEPLOY')
                          + REWARD(IO));

 INPORT(I)=SUM((P,B,IO),PREV(I,P,B,IO));
```

```
*-------------------------------------------------------------------
          DECISION VARIABLES
*-------------------------------------------------------------------


BINARY VARIABLES     S(I,P,B,IO,T);

POSITIVE VARIABLES
 ZP(I,P,B,IO,T);

VARIABLES            UTILITY;

*-------------------------------------------------------------------
*                      FORMULATION
*-------------------------------------------------------------------

EQUATIONS

    SUCCESS  EQUATION THAT MEASURES THE SUCCESS OF BERTHING SCHEDULE
    PIERLEN(P,T) SUM OF SHIPS LENGTH MUST BE LESS THAN PIER LENGTH
    POWER(P,T)  PIER POWER CABLE EQUATION FOR EACH TIME PERIOD
    SHIPCOM(P,B,T) OUTBOARD SHIP LENGTH MUST BE LESS INBOARD SHIP
    SHIPCOM1(P,B,T) OUTBOARD1 SHIP LENGTH LESS RHAN OUTBOARD SHIP
    ENSURE(I,T) ASSIGN EACH SHIP TO ONE BERTH IF THE SHIP IS IN
    ENSURE1(P,B,T) ASSIGN AT MOST THREE SHIPS PER BERTH
    ENSURE2(P,B,IO,T) ASSIGN ONLY ONE SHIP TO ONE SPOT
    CHKDAY1(I,P,B,IO) PENALTY FOR BERTH SHIFT FOR DAY 1
    CHECK1(I,P,B,IO,T) PENALTY FOR BERTH SHIFT
    OUTBLIM(I,P,B,IO,T) ENSURES IDENTIFIED SHIPS HAVE NOONE OUTBOARD
    BASINLIM(BASIN,B,T) WIDTH OF SHIPS PLUS ROOM FOR TUG IN BASIN;

SUCCESS..

 UTILITY =E=  SUM((I,P,B,IO,T)$COMPAT(I,P,B,IO,T),
                 S(I,P,B,IO,T)*BENEFIT(I,P,B,IO,T))
            - SUM((I,P,B,IO,T)$((COMPAT(I,P,B,IO,T) EQ 1) AND
                (SHIPDATA(I,'ARRIVE') LT ORD(T))),
               SHIPDATA(I,'COSTSHF')*ZP(I,P,B,IO,T))
            -SUM((I,P,B,IO)$(COMPAT(I,P,B,IO,'D1') EQ 1 AND
    PREV(I,P,B,IO) EQ 1),SHIPDATA(I,'COSTSHF')*ZP(I,P,B,IO,'D1'));


PIERLEN(P,T)..

      SUM((I,B)$COMPAT(I,P,B,'INBD',T),
        ( SHIPDATA(I,'LENGTH')+BETWEEN)*S(I,P,B,'INBD',T))-S1(P,T)
             =L=  PIERDATA(P,'PIERL')+EXTEND;


CHKDAY1(I,P,B,IO)$(COMPAT(I,P,B,IO,'D1') GE 1 AND PREV(I,P,B,IO)
                                                             EQ 1)..
       S(I,P,B,IO,'D1')+ZP(I,P,B,IO,'D1') =G= PREV(I,P,B,IO);
```

```
 CHECK1(I,P,B,IO,T)$(ORD(T) GT 1 AND
          SHIPDATA(I,'ARRIVE') LT ORD(T) AND
                     COMPAT(I,P,B,IO,T) GT 0)..

 S(I,P,B,IO,T)-(COMPAT(I,P,B,IO,T-1)*S(I,P,B,IO,T-1))-ZP(I,P,B,IO,T)
                                                                =L=0;

 POWER(P,T)..

            SUM((I,B,IO)$COMPAT(I,P,B,IO,T),
    S(I,P,B,IO,T)*SHIPDATA(I,'SHIPPWR'))-S2(P,T)=L=PIERDATA(P,'POWER');

SHIPCOM(P,B,T)
         $( SUM(I,COMPAT(I,P,B,'OUTBD',T)) GT 0)..

             SUM(I$COMPAT(I,P,B,'INBD',T),
      S(I,P,B,'INBD',T)*SHIPDATA(I,'LENGTH'))=G=
             SUM(I$COMPAT(I,P,B,'OUTBD',T),
                 S(I,P,B,'OUTBD',T)*SHIPDATA(I,'LENGTH'));


SHIPCOM1(P,B,T)
       $(SUM(I,COMPAT(I,P,B,'OUTBD1',T)) GT 0)..

             SUM(I$COMPAT(I,P,B,'OUTBD',T),
     S(I,P,B,'OUTBD',T)*SHIPDATA(I,'LENGTH'))=G=
             SUM(I$COMPAT(I,P,B,'OUTBD1',T),
                 S(I,P,B,'OUTBD1',T)*SHIPDATA(I,'LENGTH'));


ENSURE(I,T)$(SUM((P,B,IO),COMPAT(I,P,B,IO,T)) GE 1)..

     SUM((P,B,IO)$COMPAT(I,P,B,IO,T),S(I,P,B,IO,T)) =E= 1;


ENSURE1(P,B,T)
   $(SUM((I,IO),COMPAT(I,P,B,IO,T)*(SHIPDATA(I,'SHP')-1)) GT 2)..

   SUM((I,IO)$COMPAT(I,P,B,IO,T),
                  SHIPDATA(I,'SHP')*S(I,P,B,IO,T)) =L= 3;


ENSURE2(P,B,IO,T)$(SUM(I,COMPAT(I,P,B,IO,T)) GT 1)..

 SUM(I$COMPAT(I,P,B,IO,T), S(I,P,B,IO,T))-S5(P,B,IO,T) =L= 1;
```

```
 BASINLIM(BASIN,B,T)$(SUM(P,BELONG(BASIN,P)) GT 0
  AND SUM((I,P,IO),COMPAT(I,P,B,IO,T)*BELONG(BASIN,P)) GT 1)..

   SUM((I,P,IO)$COMPAT(I,P,B,IO,T),
   S(I,P,B,IO,T)*(SHIPDATA(I,'BEAM')+FENDER)*BELONG(BASIN,P))
                      =L= BWIDTH(BASIN)-TUGWIDTH;

 OUTBLIM(I,P,B,IO,T)$(NOOUT(I) EQ 1 AND ORD(IO) LT 3
    AND COMPAT(I,P,B,IO,T) EQ 1)..
    (3-ORD(IO))*S(I,P,B,IO,T)-COMPAT(I,P,B,IO+1,T)*S(I,P,B,IO+1,T)
       -COMPAT(I,P,B,IO+2,T)*S(I,P,B,IO+2,T)
   +SUM(IP $COMPAT(IP,P,B,IO+1,T),S(IP,P,B,IO+1,T))
    +SUM(IP $COMPAT(IP,P,B,IO+2,T),S(IP,P,B,IO+2,T))=L=(3-ORD(IO));


MODEL SHIP1 /ALL/;
OPTION LIMROW=0, LIMCOL=0, OPTCR=.0, ITERLIM=50000, RESLIM=2500;
OPTION SOLPRINT = On, SYSOUT = Off;
SOLVE SHIP1 USING MIP MAXIMIZING UTILITY;
DISPLAY S.L;
 PARAMETER SOL(I,P,B,IO);
 OPTION SOL:1:1:3;

 DAY = 1;

LOOP(T,
       SOL(I,P,B,IO) =  S.L(I,P,B,IO,T);
       DISPLAY DAY, SOL;
      DAY = DAY +1);
```

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11. Department Chairman, Code 55 1
Department of Operations Research
Naval Postgraduate School
Monterey, California 93943-5000

12. Dr. David Ronen 1
School of Business Administration
8001 Natural Bridge Road
Saint Louis, Missouri 63121-4499